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A review on potential applications of carbon nanotubes in marine current turbines

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ABSTRACT

Marine current turbine is one of the promising marine renewable energy technologies that could provide clean and sustainable energy. This field has undergone rapid growth in both industry and academia during the last decade. However, there was no study being done in incorporating nanotechnology into marine current turbines. Carbon nanotubes, as one of the most studied nanomaterials, are a potential candidate to be incorporated into marine current turbines. This paper aims to review some of the researches done on carbon nanotubes to date, and proposed some potential applications in marine current turbines based on the review. The potential applications proposed are based on the need of marine current turbines. Apart from that, it also aims to act as a starting point to connect the two research areas (marine renewable energy and nanotechnology) together. The proposed applications include: structural reinforcement, fouling release coating, structural health monitoring, high performance wires/cables and lubrication.

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Contents

1. Introduction

Marine renewable energy as one of the renewable energy sources has gained attention from European countries and US since 1970s [1]. However, limited researches and studies were conducted in this field until the last decade [2]. Generally, types of marine renewable energy can be categorised into tidal, wave, current, ocean temperature gradient, salinity gradient and offshore wind. [1,2]. Offshore wind is a product of the interaction between the heat from the ocean surface and the atmosphere above it. This is the reason for categorising offshore wind as part of the marine renewable energy. These energy sources, especially tidal, wave and current, are said to possess greater potential in generating electricity compared with other renewable energies, as they are relatively consistent and predictable [3–6].

The rapid growth of marine renewable energy in the last decade, both in industry and academia, can be seen from the Annual Reports published by Ocean Energy Systems Implementing

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Agreement (OES-IA) of the International Energy Agency (IEA) [7–9], and review papers published by various researchers around the world [10–13]. Although most of the works are still in prototype testing phase, the commercialisation of some systems like tidal current and wave is already in progress [14–16]. Despite the rapid growth, to the best of authors' knowledge, no study has been carried out in incorporating nanotechnology into marine renewable energy technology. In fact, such an idea was mentioned a decade ago [17] and some possible applications of nanotechnology in marine renewable energy technology were suggested.

Nanotechnology, which utilises the special characteristics possessed by various nanomaterials, is well known in some renewable energy fields and environmental applications such as: photovoltaic cell, clean energy production and storage, catalyst for air treatment and wastewater treatment [18–20]. However, application of nanotechnology in marine renewable energy devices is rarely seen either in industry or academia. To date, there is only research in studying carbon nanotubes for wind turbine blade [21–24]. Viewing that the offshore wind is part of the marine renewable energy, these research works can be considered as pioneering study towards actual application of nanotechnology in marine renewable energy field.

As previously mentioned, the idea of using nanotechnology in marine renewable energy field is not new. However, detailed discussions and studies in integrating which nanotechnology with which marine renewable energy devices (exclude offshore wind) are limited or nearly zero. Hence, this paper aims to review and to propose possible applications of nanotechnology in marine renewable energy. Marine current turbine as one of the marine renewable energy technologies has undergone rapid growth in the last decade [25]. But to the best of authors' knowledge, no study has been done in incorporating nanotechnology into marine current turbines. Hence, marine current turbine is selected for this study. The selected nanotechnology is the carbon nanotubes, as it is one of the most studied nanomaterials and its applications cover a wide range of areas.

2. Characteristics of carbon nanotubes

The world has started to pay attention on carbon nanotubes since the report of multi-walled carbon nanotubes by Iijima in 1991 [26], and single-walled carbon nanotubes by Iijima et al. and Bethume et al. simultaneously in 1993 [27,28]. Carbon nanotube is a material consists of pure carbon atom which exists in tube shape. For single-walled carbon nanotubes, it is like rolling a monoatomic layer of carbon into a cylinder. Whereas multi-walled carbon nanotubes are made of more single-walled carbon nanotubes arranged concentrically. The average diameter of a single-walled carbon nanotube is about 1–2 nm, while a multi-walled carbon nanotube can be more than 50 nm [29,30]. Generally, the length of carbon nanotubes can be in the range of micrometre or even millimetre, and this gives carbon nanotubes a high aspect ratio.

Based on the configuration of the carbon, carbon nanotubes can be further categorised into three structures, namely armchair, zigzag and helical. The properties of carbon nanotubes vary depending on these structures [30]. There are many methods used to synthesise carbon nanotubes such as: laser ablation, electric arc method and catalytic chemical vapour deposition (CVD). But, it is still difficult to specifically synthesise any of these structures alone through a controllable way at the moment [31]. Therefore, it is usual to get a bundle of carbon nanotubes comprise of all these structures in bulk production. Nevertheless, the orientation of the carbon nanotubes can be controlled to form vertically aligned array [29]. This type of highly ordered orientation also has effect on the final properties of the carbon nanotubes.

2.1. Mechanical properties

One of the most spectacular properties of carbon nanotubes is its mechanical properties. Theoretically, it was calculated that the tensile strength can be as high as 45 GPa for single-walled carbon nanotube [32] and 150 GPa for perfect multi-walled carbon nanotube [33]. But, the direct measured tensile strength reported was far lower than these values. Li and co-workers reported that the tensile strength for one single-walled carbon nanotube is around 22 GPa [34]. The tensile strength of a single-walled carbon nanotube bundle was estimated to be around 14 GPa and lower. In another work reported by Yu and co-workers, the measured tensile strength for multi-walled carbon nanotube is within the range of 11–63 GPa only [35]. This suggests that the bulk production produced carbon nanotubes would have a tensile strength of about 10–20 GPa.

As a comparison, the tensile strength of high strength steel is about 1–2 GPa [33]. This means that carbon nanotube is at least 5 times stronger than high strength steel. Yet, the density of single-walled carbon nanotube reported is about 1.33–1.40 g/cm^3, which is almost only half the density of aluminium [36]. Owing to the strong and lightweight properties, carbon nanotube can be used as reinforcing agent to create high strength composite materials without significant effect towards the final weight of the product [30,37,38]. A worth noticing thing is that different structure can give different strength properties (armchair has better tensile strength compared with zigzag and helical [39]). When the synthetic methods become more mature, it is possible to produce carbon nanotubes with higher strength, which comprised mainly or wholly of armchair structure.

2.2. Chemical properties

The nature of the carbon nanotubes' seamless cylindrical wall makes it chemically stable under room temperature. Generally, the chemical reactivity on the open end of carbon nanotube is higher than the side wall [40–42]. It is possible to functionalise carbon nanotubes for various desired applications by attaching functional groups to nanotubes through appropriate treatment [43,44]. In fact, such functionalisation is essential to improve the processability of carbon nanotubes, in order to couple its properties with other materials [45]. The chemical stability, coupled with the high surface area (given by the outer wall and the inner wall of the tube) also makes carbon nanotube a potential candidate for adsorption and storage application [46,47]. Specifically, research community is keen to utilise carbon nanotube for hydrogen storage purpose.

Pure single-walled carbon nanotubes do not disperse in water or organic solvent due to the strong Van der Waals force between individual carbon nanotubes [48], hence, making carbon nanotubes to be hydrophobic. The hydrophobicity of carbon nanotubes can be further enhanced by creating highly ordered vertically aligned carbon nanotubes. For such carbon nanotubes array or forest, their hydrophobicity is a result of the micro- or nano-scale hierarchical roughness [49]. When the water touches the surface of carbon nanotubes array, it will be supported by the nano-air bubbles entrapped within the array, hence resulting in the hydrophobic phenomenon. Since such mechanism depends on the surface structure, other nanomaterials (capable of forming aligned arrays) can also be utilised to create this type of hydrophobic surface.

2.3. Electrical properties

Carbon nanotubes as a one-dimensional system also possess unique electrical properties. Generally, single-walled carbon nanotubes

can be metallic or semiconducting based on the diameter and chiral indices, while multi-walled carbon nanotubes are metallic [50,51]. The mobility of charge carrier of a single-walled carbon nanotube can goes up to 10,000 cm^2/Vs. As a comparison, the mobility of charge carrier of silicon is about 1,000 cm^2/Vs. In addition, the current carrying capacity of a single-walled carbon nanotube is about 4×10^9 A/cm^2 [52,53]. This capacity is several orders of magnitude higher than copper. These properties make carbon nanotubes a potential material to replace silicon in the chip manufacturing. If carbon nanotubes were used to make wires or cables, the wires/cables are expected to have higher data transmission ability [36,54,55].

The high current carrying capacity also indicates that the electrical resistivity of carbon nanotubes is low. McEuen and co-workers reported that a single-walled carbon nanotube has a resistivity of 10^{-6} Ωcm [56]. On the other hand, Bachtold and co-workers reported the resistivity of a multi-walled carbon nanotube to be about 3×10^{-5} Ω cm [57]. The resistivity of carbon nanotubes is structure-sensitive [58]. Deformation of carbon nanotube would alter the resistivity significantly. Another worth noticing properties of carbon nanotubes that coupled nicely with the abovementioned electrical properties is the thermal conductivity. The thermal conductivity of an isolated single walled carbon nanotube was predicted to be around 6000 W/m-K [36,59,60]. This high heat transmission property also makes it a potential heat managing material for microchips [61,62].

2.4. Implementation considerations

The spectacular properties possessed by carbon nanotube make it a potential candidate for a wide range of applications. However, full utilisation has yet to be realised due to some limitations. The properties of carbon nanotube are highly dependent on the purity and structure. At this stage, the method used for bulk production of carbon nanotubes is the CVD method. Although the CVD method is capable of producing large amount of single-walled and multi-walled carbon nanotubes with reasonable cost, the carbon nanotubes produced by this method have a greater number of defects [35,63] compared with other methods. This indicates that the actual properties of pure carbon nanotubes could not be realised for many of the potential applications suggested by researchers at the moment.

Apart from the defects issue, the dispersion of carbon nanotubes is also an obstacle. For instance, ideally, carbon nanotubes must be uniformly dispersed in the composite material to achieve better reinforcing effect. However, the CVD method always produces carbon nanotubes in bundle. Normally, ultrasonication is used to disperse carbon nanotubes in solvents. This process is rather slow and probably reversed when the sonication stops [64,65]. Last year, Yang and co-workers had demonstrated the use of hydrogen passivation and ultrasonication to uniformly disperse multi-walled carbon nanotubes [66]. It was claimed that the carbon nanotubes/epoxy composite produced using this method has better mechanical properties compared with carbon nanotubes/epoxy composite produced by other methods. Nevertheless, at present, this method is yet to be adopted by industry.

As discussed in the beginning of Section 2, it is also difficult to produce carbon nanotubes with controllable structure. This is a big challenge for the utilisation of carbon nanotubes' electrical properties. Furthermore, the CVD is a catalytic based method. The products usually come with the residue of catalyst. Such impurities not only affect the properties of carbon nanotubes, it also brings environmental consideration [67]. Contradict results exist in the literature and there is still no consensus on the toxicity of carbon nanotubes. Judging from the size of the carbon nanotubes alone, aerosolization of carbon nanotubes is definitely a threat for health and safety during manufacturing/handling process or accidental release, as it can transport into the respiratory system of human [68].

These manufacturing complications hinder the process of realisation of carbon nanotubes' potential applications. On the other hand, the production cost is another major obstacle that affects the acceptance of market for using this type of advanced material. According to De Volder and co-workers, the cost of the bulk multi-walled carbon nanotubes produced by the CVD method is still higher than the carbon fibre available in the market. Moreover, the production cost of single-walled carbon nanotubes is also several orders of magnitude higher than multi-walled carbon nanotubes [69]. As a result, carbon nanotubes are somehow less competitive compared to other materials and this causes the production cost of carbon nanotubes remain high for the time being. Contrarily, carbon nanotubes can still be competitive for small scale application with a lower cost. Readers are referred to [69] for current advance in carbon nanotubes.

Certainly, these obstacles limit the usage of carbon nanotubes in industry at the moment. There is always trade-off for an immature technology. For instance, the quality of carbon nanotubes is compromised for bulk and cost effective production. Nonetheless, it is just a matter of time to realise the potential applications of carbon nanotube. Same goes with the potential applications of carbon nanotubes in marine current turbines, which will be discussed in the following sections. Carbon nanotubes can potentially enhance marine current turbines in many aspects and helps in overcoming certain challenges. However, the obstacles discussed in this section will definitely limit the utilisation of carbon nanotubes. In some cases, other nanotechnology/nanomaterials might work better than carbon nanotubes (see Section 4).

3. Potential applications of carbon nanotubes

The concept of extracting energy from ocean current or tidal current by using marine current turbines is similar to the concept of extracting energy from wind flow by using wind turbines. The aim is to harness the kinetic energy of the flowing fluid by using a turbine with two or more blades. To some extent, the fundamental theories used in estimating the dimensions of turbines or energy extraction, such as the actuator disc theory, are applicable for both wind turbines and marine current turbines [70,71]. Currently, several large scale marine current turbines with different designs have been deployed (majority under testing), and almost all of them are of horizontal-axis type. For examples, twin rotor two-bladed turbines (SeaGen) by Marine Current Turbines Ltd., three-bladed turbine by Atlantis Resources Ltd. and Open-Centre tidal turbine by OpenHydro [7–9]. Hence, all the discussion in this paper will focus on horizontal-axis type turbine.

The transfer of technology from wind turbines to marine current turbines is rationally acceptable, since the concept and theories are quite similar. Furthermore, wind energy sector possesses relatively matured technology to be used as a reference for marine current energy. It may be the fastest and most cost effective way to deliver the required technology for marine current turbines. Some of the transferred technologies with appropriate modifications include: the design of blades, composite material used to manufacture rotor blades and the support structure. However, the surrounding environment for marine current turbines is different from wind turbines. Ocean is a harsh environment and marine current turbine will face more challenging problems compared with wind turbine.

3.1. Reinforcement of turbine blades

The main challenges for marine current turbines include: high bending forces, cavitation, dynamic effects, the high flow velocity

fluctuation resulting from waves and turbulence, higher thrust and higher operational torque that imposed larger load to the gearbox as suggested by Fraenkel [70] and Winter [71]. Few years ago, there were cases of blade failure reported by some of the marine current turbine developers [72,73]. The prototype turbines broke into pieces during the test due to the unexpected high loading from the marine current. This indicates that the body of marine current turbines should be designed with sufficient strength to survive in the ocean. Since carbon nanotubes have long been studied as reinforcing agent to strengthen composite material, carbon nanotubes can be used as reinforcing agent to improve the strength of marine current turbines.

Taking turbine blade as example, different composite material will be used to manufacture different parts of a wind turbine blade. Those parts include: shear web, spar, root and finishing. The composite materials used include: fibreglass or carbon fibre reinforced epoxy resin and polyester resin [74,75]. As a result of technology transfer, the material used in manufacturing marine current turbines is also similar to wind turbines. According to the information accessed by authors through website, personal direct contact (personal communication, August 20, 2012) and journal articles [71,76–79], large scale marine current turbine blades were manufactured using epoxy resin and carbon fibre (also known as Prepreg material) or carbon/glass mix. To date, no carbon nanotubes or any other nanomaterials reinforced epoxy resin composite has been used in manufacturing large scale marine current turbine blade.

Research in incorporating carbon nanotubes in the epoxy matrix as a reinforcing agent had already started since late 1990s [30,80]. Researchers have investigated many different methods to synthesise carbon nanotubes reinforced epoxy resin, and studied the effect of reinforcement towards the properties of epoxy resin composite [81,82]. There were studies of carbon nanotubes incorporated carbon fibre/epoxy resin composite [83–85]. The targeted application areas are aerospace, aeronautical and naval [86,87]. So far, the results obtained by these researches show positive improvement in the mechanical properties (higher shear strength, fracture toughness and fatigue resistance) and the electrical properties (better electrical conductivity) of the enhanced epoxy resin composite.

With the improvement of shear strength and fatigue resistance, the carbon nanotubes reinforced carbon fibre/epoxy resin composite material can last longer under bending force, cyclic loads and more resistant to cavitation. Such enhanced composite material is suitable to be used in the blade body (spar cap, shear web, shell and finishing) of marine current turbines as the blade will subject to constant cyclic load and potential cavitation at the tip of blade. It is also possible to apply the material at the root part as the root of blade will also subject to high shear force and bending moment [88,89]. Apparently, carbon nanotube definitely has its potential to act as a reinforcing agent in marine current turbines, especially for the rotor blade. Simple illustrations of typical horizontal-axis marine current turbine blade are shown in Fig. 1 to give a clearer picture of the components mentioned in this and the following sections.

Similar to what the market did in transferring wind turbines technology to marine current turbines technology, the knowledge of enhanced material can also be transferred and applied in marine current turbines. However, there are challenges in turning this potential application into exact action. Different methods have been suggested to synthesise the carbon nanotubes reinforced epoxy composite, and the resulting modification of the enhanced material's properties by using different methods appears to be contradicting. One of the main challenges is the dispersion issue associated with carbon nanotubes. The reinforcement effect would not be significant if the dispersion of carbon nanotubes inside the epoxy matrix is not uniform.

3.2. Coating

Monitoring and maintenance work for marine current turbines is a big challenge as the device is submerged in the ocean. One of the challenges is the attachment of marine microorganisms on the body of marine current turbines. The formation of the microorganisms' colonies is known as the bio-fouling. According to recent tests, it was found that carbon fibre/epoxy resin composite has a higher chance to foul and deteriorate [90,91]. Although the tests results are highly site specific, the general behaviour should be more or less analogous. Since this composite material is currently one of the main materials used in manufacturing marine current turbine blade, this implies that the bio-fouling issue might be more difficult to handle.

Bio-fouling can incurs adverse effects on marine current turbines. Fouling on the surface of the blade can cause deterioration on the blade and leads to blade failure. In addition, the presence of marine microorganisms' colonies on the blade surface will also alter the hydrodynamic design of the blade. The efficiency of energy extraction will be affected [92]. In fact, there is fouling release paint available in the market which can perform well for 3–5 yr. It is also the current practice in managing the bio-fouling problem for most of the deployed large scale marine current turbines. After the paint reaches the service life, a manual cleaning and reapplying of paint, which are both labour and cost intensive, is required to maintain the performance of marine current turbines. For those marine current turbines designed to be fixed at the seabed, without a built-in ancillary system for recovering the device to surface, the maintenance work will be even harder.

If an array of marine current turbines was to be constructed for electricity generation with a design life up to 20–30 yr (ideally for good return) [70], such fouling release paint should be more durable to minimise the maintenance frequency and cost required. The lifespan of fouling release paint depends on the intensity of fouling attack and the erosion due to collision of sediments [93]. These two issues are different in the mechanism. For fouling attack, the effectiveness of durable fouling release paint depends on the chemical properties and surface topography of applied paint that react with seawater [94,95]. For collision of sediments, it is a problem of physical erosion between free suspended solid with the coating of paint. This implies that the mechanical strength of fouling release paint towards erosion could also be enhanced by using carbon nanotubes [96].

There were limited researches in incorporating carbon nanotubes in fouling release paint or coating. The research carried out by Beigbeder and co-workers surprisingly showed that, instead of improving the mechanical properties, the presence of carbon nanotubes improves the fouling resistant (silicone based) properties through increase of hydrophobicity and a time-immersion dependent nano-topography restructuring of the coating. Nevertheless, Keshri and Agarwal reported that carbon nanotubes can enhance the wear resistance of coating [91]. Hence, the unchanged mechanical properties (as reported by Beigbeder and wo-corkers) might be caused by the amount of carbon nanotubes (0.05∼0.2 wt%) incorporated in silicone matrix was not sufficient to improve the mechanical properties of the bulk matrix [95,97,98]. Unexpectedly, the worth exploring potential of carbon nanotubes enhanced coating is not on the tribology aspect. The remarkable hydrophobicity properties of carbon nanotubes and its ability to form effective fouling release nano-topography is much worthy to be studied to enhance the fouling resistance ability of coating.

In fact, the hydrophobicity of carbon nanotubes has been studied intensively by research community [99,100]. The research focus was given to the vertically aligned carbon nanotubes array as mentioned in Section 2.2. Although research outcomes indicated that the aligned array did enhance the hydrophobicity of carbon nanotube,

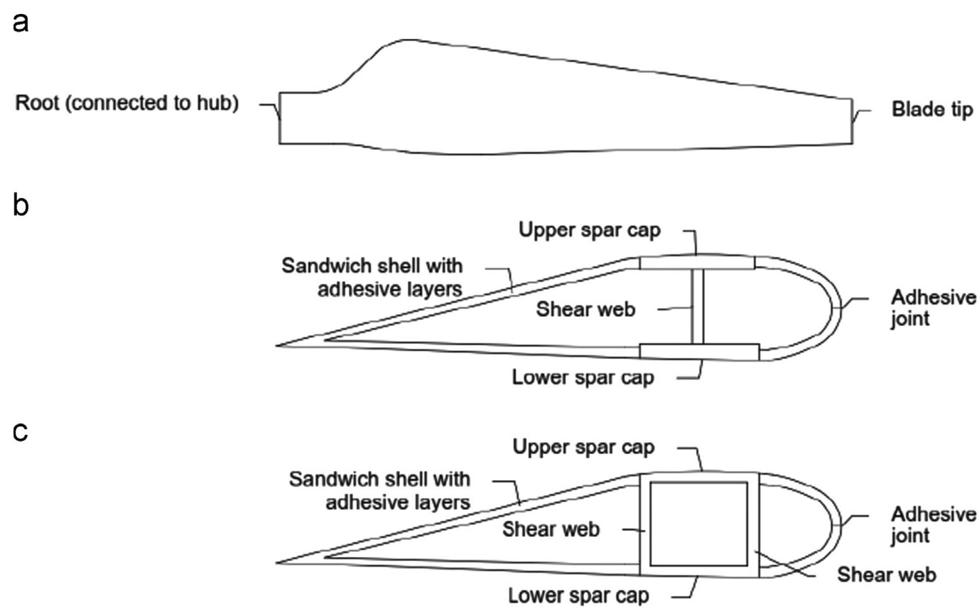

Fig. 1. (a) Plan view of blade, (b) cross section view of blade with shear web supported spar cap, and (c) cross section view of blade with box spar.

to the best of author's knowledge, there is no available literature that describes how effective of such material (with high hydrophobicity) can be towards fouling resistant/release. [49,94,101–103]. On the other hand, there is a product named BioCyl, produced by Nanocyl from Belgium, available in the market. Nanocyl claims that the BioCyl is made of upright positioned carbon nanotube (considering aligned) and tested to be effective in releasing fouling organisms like barnacles and algae [104]. The targeted market of this product is ship coating based on Nanocyl's website, and there is no sign of application of this product in marine renewable energy area yet, especially for marine current turbines.

Obviously, further research in producing fouling release paint or coating, which utilises carbon nanotubes nanostructure and hydrophobicity, is beneficial to marine current turbines in long run. However, this is a tough quest as bio-fouling is a highly localised problem and it is difficult to produce a universal multi-functional fouling release coating which can be applied under all circumstances [94]. Hence, for coating purpose, utilising the mechanical properties of carbon nanotubes to reinforce the coating for protection of some vulnerable parts seems to be more practical. For examples, protection coating for welds or seals. Cracking of these parts can leads to water contamination inside the nacelle of marine current turbines.

3.3. Structural health monitoring

As mentioned in the previous section, monitoring and maintenance work for marine current turbines can be difficult and costly. For example, monitoring structural health of the marine current turbines, either in identifying external impact damage or internal fatigues is hard to carry out. The size of marine current turbines, which is very large, makes the identification of micro-cracks to be very difficult. Furthermore, the turbine is submerged in the ocean during operation and therefore making the inspection more difficult. Deterioration of structural health of marine current turbines, especially the rotor blade, not only affects the efficiency of energy extraction, it may also lead to structural failure (the worst case). Hence, careful and high accuracy of monitoring is crucial for marine current turbines.

The research in finding a good monitoring method for structural health is common in many areas, where high performance structure is needed. Those areas include: aeronautical, automotive applications and wind turbines. Researchers are trying to develop a so called ‘smart’ material which possesses damage sensing and self-healing characteristic [105,106]. Carbon nanotubes, owning to its extraordinary multi-functionality, have also been studied to act as the sensors in such enhance ‘smart’ material. When an external force causes damage to the composite material, the internal structural deformation will deform the carbon nanotubes incorporated inside and cause changes in the resistivity of carbon nanotubes (piezoelectric effect) [107]. The concept of structural health monitoring or damage sensing is by measuring such changes of carbon nanotubes' resistivity inside the composite material.

So far, the results reported by researchers showed a good sensitivity of carbon nanotubes towards minor structural changes [108–110]. However, it requires a complex network of grid to effectively sense the resistivity changes at any desired point of the composite material, especially for in-situ damage sensing [111,112]. Hence, using carbon nanotubes enhanced damage sensing composite in marine current turbines for a large area seems to be impractical. Hence, such sensing materials would be more suitable to be applied at certain parts, which are relatively smaller. For example, the joints between the blades and hub, the adhesive layer and the adhesive joints [113]. These parts have a higher chance of suffering micro deformation or delamination. Therefore, a more sensitive damage sensor can provide early detection during monitoring. Appropriate action, such as shutting down the operation or tilting the pitch of blades, to decrease the loading can then be taken to avoid further damage that can leads to blade failure.

In fact, application of smart materials in the marine area for the purpose of structural health monitoring had already been suggested by other researchers earlier [114]. Both the marine renewable energy field and the potential of carbon nanotubes were not mentioned by that time. Based on the literatures available, carbon nanotubes did have the potential to act as a damage sensor for marine current turbines. Carbon nanotubes sensor was tested to be workable for composite joints and adhesive joint by different researchers [115,116]. The resistivity of carbon nanotubes generally changes linearly when the loading on the composite joints increase from 0% to 60% of ultimate loading [116]. Above 60% of ultimate loading, the changes deviated from linear behaviour. This result shows that carbon nanotubes can gives a very good indication of the loading condition starting from the very first loading.

It is suitable to monitor microcracks and delamination for the aforementioned small parts.

3.4. Other potential applications

The three potential applications of carbon nanotubes discussed in the previous sections are specific towards marine current turbines. Nevertheless, there are others potential applications of carbon nanotubes (studied for other fields) that could be transferred to marine current turbine as well, and help in solving the challenges of marine current turbines. This section will discuss about the high performance power transmission cables/wires made from carbon nanotubes and carbon nanotubes as lubricant additives to enhance lubricant tribology properties.

Power loss during transmission is a concern of power generation and distribution. The loss can come from the inner drive train of generator and the cable. This has serious impact on the designed electricity delivery and cost [117,118]. Researchers are trying to incorporate carbon nanotubes into the cables/wires to improve the conductivity [119,120]. There was report on successful synthesis of carbon nanotubes cables which possess higher specific conductivity compared with copper and aluminium [121]. Marine current turbines as an electricity generator will also face the challenge in power loss. Theoretically, to design a 1 MW turbine, a 1.17 MW shaft power is required after taken into account the losses derived from the system [71]. The success in developing high performance power transmission cables/wires means that the design shaft power can become lesser for marine current turbines. Consequently, the loads that bear by marine current turbines can be reduced and therefore prolongs the lifespan.

For mechanical components, tribology is a great concern. Smooth interaction between mechanical components can ensure the working efficiency of the system and the lifespan of the component. Normally, lubricant will be applied into the system to reduce the friction and wear. The performance of a lubricant is highly dependent on the additives incorporated [122,123]. Nanomaterials, as nanolubricant or additives for lubricant, have been studied to synthesis lubricant with better tribological properties, and carbon nanotube is also one of the candidates [124,125]. Successful research and development in this area will bring benefit to many fields that require high performance from the mechanical components, such as: aerospace, automobile and wind turbines. Certainly, marine current turbines can also be benefited from this.

For the issue of lubrication on marine current turbines, more concerns should be given to the prevention of lubricant leakage from the system, compared to the interest in high performance lubrication inside the nacelle of marine current turbines. Lubricant leakage is undesirable as it can cause pollution to the ocean environment. Obviously, this is a problem of structural design where the structure should be strong enough under the loadings of seawater. This is important in minimising the risk of cracks that may lead to lubricant leakage. The aforementioned structural health monitoring using carbon nanotubes might be one of the potential solutions to identify the microcracks near to those points, where lubricant leakage is possible to occur.

4. Discussions

As discussed in each potential application, there are challenges that need to be solved to realise all those applications. Apart from those technical challenges, there are two more concerns that need to be addressed too. First and foremost is the high cost associated with the production of carbon nanotubes, since the technology is still immature and a large amount of carbon nanotubes is needed. This has not yet included the processing cost for each application. The second concern is the environmental issue. As mentioned in Section 2.4, there is still no consensus among researchers regarding the toxicity of carbon nanotubes. If carbon nanotubes were incorporated in marine current turbines, escape of carbon nanotubes into the ocean might happen when there is failure. What are the effects of carbon nanotubes towards marine organisms? Will bio-accumulation occurs? What is the transport pattern of carbon nanotubes in the ocean? It might also entrap toxic chemicals in the ocean during the transport, since it has large surface area [126].

In fact, for all the main potential applications discussed, carbon nanotube is not the only method to provide the enhancement. There are other methods that can provide similar enhancement. For reinforcing purpose, the blade root can be manufactured by using metal instead of epoxy resin. Although it will suffer corrosion problem, the cost is definitely cheaper. For the hydrophobicity surface for fouling release purpose, the key factor is the surface pattern. There are many ways to produce the vertically aligned nanostructure by using other nanomaterials [127,128]. The surface patterning can even be accomplished during the moulding of blade instead of using paint. For structural health monitoring purpose, there is available methods, either been implemented or under research for wind turbines, that can be directly transferred to marine current turbines [129,130]. Otherwise, a built-in ancillary system can be built for maintenance purpose, such as the recovery system of SeaGen [78].

In view of these concerns, carbon nanotubes would not be an attracting candidate in the market for large scale marine current turbines at the moment. Contrarily, it may be more compatible with small scale marine current turbines built for remote islands. Oil price for remote islands is expensive due to logistic problems. Small scale marine current turbines may be a solution for those islands. As the size of turbines is small, the production cost will be lesser. Applications of carbon nanotubes become viable with a trade-off between production cost and maintenance cost. For example, applying carbon nanotubes may increase the production cost, but the maintenance cost saved due to the enhancement can balance it. In addition, mass production of small scale marine current turbines can further reduce the production cost too. Certainly, the alternatives mentioned in the previous paragraph can work the same, but the quality will not be as high as carbon nanotubes.

The applications of carbon nanotubes may become attractive when the technology becomes mature with a lower cost. This implementation can bring marine current turbines to a higher level. The integration of carbon nanotubes in marine current turbine might be able to improve the performance of the system directly. Taking the hydrophobic coating for example, besides providing fouling-release affects, it may also improve the hydrodynamic performance of turbine blades. Recently, researchers are interested in the friction drag reduction phenomenon induced by the hydrophobic surfaces [131,132]. Water will slip on the hydrophobic surfaces and results in a non-zero flow velocity near to an object which leads to lower friction. Such setting could potentially increase the lift and reduce the total drag of a blade. Couple with the control of angle of attack, the customised marine current turbines may operate more efficiently in the location with relatively low marine current speed.

5. Conclusion

The applications of carbon nanotube on marine current turbines have been reviewed, in order to propose the utilisation of nanotechnology in marine current energy. The proposed applications include structural reinforcement, fouling release coating, structural health monitoring, high performance wires/cables and

lubrication. It is obvious that carbon nanotubes not only help in solving problems faced by marine current turbines, it can also enhance marine current turbines directly. As a reminder, carbon nanotube is the only nanomaterial discussed here. Nevertheless, there are many other potential nanomaterials or nanotechnologies which are able to enhance marine current turbines as well. This review shows that the integration of nanotechnology in marine renewable energy is potentially viable and beneficial.

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